

# SSC EMISSION AS EXPLANATION OF THE GAMMA RAY AFTERGLOW OBSERVED IN GRB 980923

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GRB 980923 was one of the brightest bursts observed by the Burst and Transient Source Experiment (BATSE). Previous studies have detected two distinct components in addition to the main prompt episode, which is well described by a Band function. The first of these is a tail with a duration of  $\simeq 400$ s, while the second is a high-energy component lasting  $\simeq 2$  s. After summarizing the observations, we present a model for this event and conclude that the tail can be understood as the early gamma-ray afterglow from forward shock synchrotron emission, while the high-energy component is described by the SSC emission from the reverse shock. The main assumption is that of a thick-shell case from highly magnetized ejecta. The calculated fluxes, break energies, starting times and spectral index are all consistent with the observed values.

## I. INTRODUCTION

The most successful theory to explain GRBs and their afterglows is the fireball model [1]. This model predicts an expanding ultrarelativistic shell that moves into the external medium. When the expanding shell collides with another shell (internal shocks) or surrounding interstellar media (external shocks) gives rise to radiation emission through the synchrotron and SSC processes. Besides when the expanding relativistic shell encounters the external medium involves two shocks: an outgoing shock (the forward shock) and other that propagates into the ejecta (the reverse shock). When the forward shock collides with ISM, electrons are accelerated up to relativistic energies. The reverse shock heats up the shell's matter and accelerates electrons when it crosses the shell. Now, although the contribution of the synchrotron emission of reverse shock to the X-ray band could be small, electrons in the reverse shock region can upscatter the synchrotron photons (SSC process) up to higher energies. In this work we extend the smooth tail work done by [2] and study synchrotron self-inverse Compton radiation from a thick shell of reverse shock fireball to explain the hard component of the GRB 980923.

## II. GRB 980923

GRB 980923 was observed by BATSE on 1998 September 23 at 20:10:52 UT for 32.02 s. It was localized to 2340 with respect to the pointing-axis direction of CGRO. In accordance to [3], the event consists of three components [4]. The first component is related to the typical prompt emission, the second one is related to the smooth tail which lasts 400s and the last one is related to the hard component which shows a high energy spectral component extending up to 150 MeV and the power index  $-1.44 \pm 0.07$ . The smooth tail was well described by [2] as the evolution of a

synchrotron cooling break in the slow-cooling regime at  $t_0=32$  seconds where the characteristic value of the power index was  $p=2.4 \pm 0.11$ . However, [3] point out that the tail could begin before or at least about 14s after the burst trigger and after of a short period of time occurred the transition between fast to slow cooling.

## III. DYNAMICS OF THE FORWARD AND REVERSE SHOCK

In a unified way between forward and reverse shock, we compute the energy range for synchrotron self-inverse Compton radiation from a thick shell of the reverse shock fireball to explain the hard component. The subscripts f and r refer throughout to the forward and reverse shock, respectively.

### A. Smooth tail from Synchrotron radiation forward shock

For the forward shock, we assume that electrons are accelerated in the shock to a power law distribution of Lorentz factor  $\gamma_e$  with a minimum Lorentz factor  $\gamma_m$ :  $N(\gamma_e)d\gamma_e \propto \gamma_e^{-p}d\gamma_e$ ,  $\gamma_e \geq \gamma_m$  and that constant fractions  $\epsilon_{e,f}$  and  $\epsilon_{B,f}$  of the shock energy go into the electrons and the magnetic field, respectively. Then

$$\begin{aligned}\gamma_{m,f} &= \epsilon_{e,f} \left( \frac{p-2}{p-1} \right) \frac{m_p}{m_e} \gamma_f \\ &= 524.6 \epsilon_{e,f} \gamma_f\end{aligned}\quad (1)$$

where we have used the value of  $p=2.4 \pm 0.11$  as was obtained by [2]. Using the typical parameters given by [5], we compute the typical and cooling frequencies of the forward shock synchrotron emission [6] which are given by,

$$\nu_{m,f} \sim 1.9 \times 10^{19} \left( \frac{1+z}{2} \right)^{1/2} \left( \frac{\epsilon_{e,f}}{0.95} \right)^2 \epsilon_{B,f,-5}^{1/2}$$

$$\begin{aligned}
\nu_{c,f} &\sim 3.0 \times 10^{19} \left( \frac{1+z}{2} \right)^{-1/2} \left( \frac{1+x_f}{2.5} \right)^{-2} \\
&\quad \epsilon_{B,f,-5}^{-3/2} n_{f,0}^{-1} E_{54}^{-1/2} t_1^{-1/2} \text{ Hz} \\
F_{\max,f} &\sim 2.2 \times 10 \left( \frac{1+z}{2} \right) \epsilon_{B,f,-5}^{1/2} n_{f,0}^{1/2} D_{28}^{-2} E_{54} \mu\text{Jy} \\
t_{\text{tr},f} &\sim 8.7 \left( \frac{1+z}{2} \right) \left( \frac{\epsilon_{e,f}}{0.95} \right)^2 \epsilon_{B,f,-5}^2 n_{f,0} E_{54} \text{ s} \quad (2)
\end{aligned}$$

where the convention  $Q_x = Q/10^x$  has been adopted in cgs units throughout this document unless otherwise specified.  $t_{\text{tr},f}$  is the transition time, when the spectrum changes from fast cooling to slow cooling,  $D$  is the luminosity distance,  $n_f$  is the ISM density,  $t$  is the time of the evolution of the tail,  $E$  is the energy, and the term  $(1+x_f)$  was introduced because a once-scattered synchrotron photon generally has energy larger than the electron mass in the rest frame of the second-scattering electrons. Multiple scattering of synchrotron photons can be ignored.  $x_f$  is given by [22] as:

$$x_f = \begin{cases} \frac{\eta \epsilon_{e,f}}{\epsilon_{B,f}}, & \text{if } \frac{\eta \epsilon_{e,f}}{\epsilon_{B,f}} \ll 1, \\ \left( \frac{\eta \epsilon_{e,f}}{\epsilon_{B,f}} \right)^{1/2}, & \text{if } \frac{\eta \epsilon_{e,f}}{\epsilon_{B,f}} \gg 1. \end{cases} \quad (3)$$

where  $\eta = (\gamma_{c,f}/\gamma_{m,f})^{2-p}$  for slow cooling and  $\eta = 1$  for fast cooling.

From eq. (2), we observe directly that  $\nu_{m,f} \leq \nu_{c,f}$ , the break energy  $E_{c,f} \sim 124.1 \text{ keV}$  and  $t_{\text{tr},f} \sim 8.7$ , implying also that the transition from fast to slow cooling could take place on very short timescales, comparable to the duration of the burst.

## B. X ray flare from thick shell Reverse shock

For the reverse shock, it is possible to obtain a simple analytic solution in two limiting cases, thin and thick shell, [7] by using a critical Lorentz factor  $\Gamma_c$ ,

$$\begin{aligned}
\Gamma_c &= \left( \frac{3E}{4\pi n_r m_p c^5 T^3} \right)^{1/8} \left( \frac{1+z}{2} \right)^{3/8} \\
&= 255.2 \left( \frac{1+z}{2} \right)^{3/8} n_{r,1}^{-1/8} E_{54}^{1/8} \left( \frac{T_{90}}{32s} \right)^{-3/8} \quad (4)
\end{aligned}$$

where  $T_{90}$  is the time of the GRB, which is much larger than the peak time of the reverse shock emission, and  $n_r$  is the thick shell density. We consider the thick shell case in which the reverse shock becomes relativistic during the propagation and the shell is significantly decelerated by the reverse shock. Hence, the Lorentz factor at the shock crossing time  $t_c$  is given by  $\gamma_d \sim \Gamma_c$  [8, 9] and for  $\sigma = L_{pf}/L_{kn} \sim 1$  the crossing

time  $t_c$  is much shorter than  $T_{90}$ ,  $t_c \sim T_{90}/6$ , [10–13]. Now, if the constant fractions,  $\epsilon_{e,r}$  and  $\epsilon_{B,r}$  of the reverse shock energy go into the electrons and magnetic fields, respectively, we have

$$\begin{aligned}
\gamma_{m,r} &= \epsilon_{e,r} \left( \frac{p-2}{p-1} \right) \frac{m_p}{m_e} \frac{\gamma_r}{\Gamma_c} \\
&= 1233.5 \left( \frac{1+z}{2} \right)^{-3/8} \left( \frac{\epsilon_{e,r}}{0.6} \right) \gamma_{r,3} n_{r,1}^{1/8} E_{54}^{-1/8} \left( \frac{T_{90}}{32s} \right)^{3/8} \quad (5)
\end{aligned}$$

where  $\gamma_r$  is the Lorentz factor of the thick shell. The spectral characteristics of the forward and reverse shock synchrotron emission are related [8, 10, 14–17] by,

$$\begin{aligned}
\nu_{m,r} &\sim \mathcal{R}_e^2 \mathcal{R}_B^{-1/2} \mathcal{R}_M^{-2} \nu_{m,f} \\
\nu_{c,r} &\sim \mathcal{R}_B^{3/2} \mathcal{R}_x^{-2} \nu_{c,f} \\
F_{\max,r} &\sim \mathcal{R}_B^{-1/2} \mathcal{R}_M F_{\max,f} \quad (6)
\end{aligned}$$

where  $\mathcal{R}_B = \epsilon_{B,f}/\epsilon_{B,r}$ ,  $\mathcal{R}_e = \epsilon_{e,r}/\epsilon_{e,f}$ ,  $\mathcal{R}_x = (1+x_f)/(1+x_r+x_r^2)$  and  $\mathcal{R}_M = \Gamma_c^2/\gamma$ . The previous relations tell us that including the re-scaling there is a unified description between both shocks (forward and reverse). Such as the magnetic field where there are some central engine models[19–21] for which the fireball wind may be endowed with "primordial" magnetic fields. Also as the cooling Lorentz factor must be corrected, then  $\mathcal{R}_x$  is introduced as a correction factor for the IC cooling, where  $x_r$  is obtained by [8] as,

$$x_r = \begin{cases} \frac{\eta \epsilon_{e,r}}{\epsilon_{B,r}}, & \text{if } \frac{\eta \epsilon_{e,r}}{\epsilon_{B,r}} \ll 1, \\ \left( \frac{\eta \epsilon_{e,r}}{\epsilon_{B,r}} \right)^{1/3}, & \text{if } \frac{\eta \epsilon_{e,r}}{\epsilon_{B,r}} \gg 1. \end{cases} \quad (7)$$

Using equations (2) and (6), the typical and cooling frequencies of the reverse shock synchrotron emission are

$$\begin{aligned}
\nu_{m,r} &\sim 3.4 \times 10^{16} \left( \frac{1+z}{2} \right)^{-1} \left( \frac{\epsilon_{e,r}}{0.6} \right)^2 \left( \frac{\epsilon_{B,r}}{0.125} \right)^{1/2} \\
&\quad \gamma_{r,3}^2 n_{r,1}^{1/2} \text{ Hz}, \\
\nu_{c,r} &\sim 1.5 \times 10^{11} \left( \frac{1+z}{2} \right)^{3/2} \left( \frac{1+x_r+x_r^2}{6} \right)^{-2} \\
&\quad \left( \frac{\epsilon_{B,r}}{0.125} \right)^{-7/2} n_{r,1}^{-3} E_{54}^{-1/2} \gamma_{r,3}^{-6} \left( \frac{T_{90}}{32s} \right)^{5/2} \text{ Hz}, \\
F_{\max,r} &\sim 5.02 \times 10^2 \left( \frac{1+z}{2} \right)^{7/4} \left( \frac{\epsilon_{B,r}}{0.125} \right)^{1/2} n_{r,1}^{1/4} D_{28}^{-2} E_{54}^{5/4} \\
&\quad \gamma_{r,3}^{-1} \left( \frac{T_{90}}{32s} \right)^{-3/4} \text{ Jy}. \quad (8)
\end{aligned}$$

From equation (8) we see that  $\nu_{m,r}$  and  $\nu_{c,r}$  correspond to optical and IR frequencies, respectively. However these energies were not recorded. Instead, as

higher energy photons were observed we compute the upscattering emission of the synchrotron radiations by relativistic electrons [22]),

$$\begin{aligned}
 \nu_m^{(IC)} &\sim 1.034 \times 10^{23} \left( \frac{1+z}{2} \right)^{-7/4} \left( \frac{\epsilon_{e,r}}{0.6} \right)^4 \left( \frac{\epsilon_{B,r}}{0.125} \right)^{1/2} \\
 &\quad \gamma_{r,3}^4 n_{r,1}^{3/4} E_{54}^{-1/4} \left( \frac{T_{90}}{32s} \right)^{3/4} \text{ Hz}, \\
 \nu_c^{(IC)} &\sim 1.1 \times 10^{10} \left( \frac{1+z}{2} \right)^{3/2} \left( \frac{1+x+x^2}{6} \right)^{-4} \\
 &\quad \left( \frac{\epsilon_{B,r}}{0.125} \right)^{-7/2} n_{r,1}^{-3} E_{54}^{-1/2} \gamma_{r,3}^{-6} \left( \frac{T_{90}}{32s} \right)^{-5/2} \text{ Hz}, \\
 F_{\max}^{(IC)} &\sim 4.7 \times 10^{-2} \left( \frac{1+z}{2} \right)^{9/4} \left( \frac{\epsilon_{B,r}}{0.125} \right)^{1/2} n_{r,1}^{3/4} D_{28}^{-2} \\
 &\quad E_{54}^{7/4} \gamma_{r,3}^{-2} \left( \frac{T_{90}}{32s} \right)^{-5/4} \text{ Jy}.
 \end{aligned} \tag{9}$$

From equation (9) we observe the break energies and  $(\nu F)_{\max} = 21.2 \times 10^{-6} \frac{erg}{cm^2 s}$  are within the range pointed out by [3, 23].

#### IV. DISCUSSION AND CONCLUSIONS

Choosing  $t_0 \leq 14s$  [3, 4, 23], and assuming that from this time until  $t \sim 32s$  the synchrotron emission was eclipsed by the prompt, the transition time between fast and slow cooling is  $\sim 8.7s$ , so 18s later the synchrotron process generated by the forward shock was in the slow-cooling regime and the energy range obtained corresponds to that reported by [2]. Also, we suggest that the diminishing flux at  $\simeq 14s$  may be due to pair production ( $\gamma\gamma \rightarrow e^+e^-$ ) between prompt emission and forward shock photons (equation 2) at the beginning of the first second.

In the reverse shock, the synchrotron process emitted photons with  $\nu_{c,r} \sim 1.0 \times 10^{10} \text{ Hz}$  and  $\nu_{m,r} \sim 4.6 \times 10^{16} \text{ Hz}$ , which were not recorded but were up-scattered by electrons up to break energies  $E_c^{IC} \sim 4.2 \times 10^{-5} \text{ eV}$ ,  $E_m^{IC} \sim 427.9 \text{ MeV}$  with a  $(\nu F)_{\max} = 21.2 \times 10^{-6} \frac{erg}{cm^2 s}$ , which were pointed out by [3, 23]

and [4]. Now, in accordance with the observed value for the power index  $\beta \sim 1.44 \pm 0.07$ ,  $\nu_{m,r}^{(ic)} > \nu_{c,r}^{(ic)}$  we conclude the SSC spectrum corresponds to fast-cooling regime, very similar to GRB 941017 [24, 25]. For our case (thick case), the flare occurs during the prompt gamma-ray phase.

In accordance with  $\mathcal{R}_B$ , we obtained that forward and reverse magnetic fields are related by  $B_f = 0.9 \times 10^{-3} B_r$ . The previous result indicates that there was a stronger magnetic field in the reverse-shock region than in the forward shock region, which may suggest that the obtained results are given when the ejecta is magnetized, as in the interpretation of the early afterglow of GRB 990123 and GRB 021211 provided by [14].

Finally, because the Large Area Telescope (LAT) covers the energy range from about 20 MeV to more than 300 GeV, we hope to detect other hard components in GRBs and so further constrain this model.

The current model accounts for the main characteristics of the burst: energies, spectral indices, fluxes, duration of the main components in a unified manner. The main requirements are that the ejecta be magnetized, leading to the formation of a reverse shock. The model has eight free parameters (equipartition magnetic field, equipartition electron energy, Lorentz factor, and densities all of the in the reverse and forward shocks), with standard values.

This burst has similar characteristics to GRB 090926A [26], but the high energy extended emission component may require SSC from the forward shock [27].

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